Simulation of Control Options for HVAC Management of a Typical Office Building

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Abstract:
An investigation of correction of defects, as Energy Conservation Opportunities (ECOs) in HarmonAC project, can be done to fulfill two objectives: to improve thermal comfort and to reduce energy consumption of buildings.
Among defect correction, HVAC control appears as a way of significant improvement.
HVAC control is examined by using a dynamic simulation to improve the management of HVAC system for two opportunities: centrally, one opportunity is to sequence better Winter and Summer mode; locally, another one is the modification of internal set points to adapt to external climatic conditions. Adaptive comfort is examined to develop new rules for local control.
Energy impact and thermal comfort of these two ECOs is investigated in the paper.
An analysis of thermal comfort criterion shows that applying the operative temperature of EN15251 increases the consumption of the simulated building compared with a simple temperature control.
According to our definition of heating and cooling modes, a good management of water network pumps for a four pipes system can reduce their consumption by 33%.
A method to determine heating and cooling seasons is proposed to provide sufficient thermal comfort.
A proposal to model the reasoned use of air conditioning equipment are investigated, it achieves a good thermal comfort and reduces the cooling load by 7% for Liege location.

Keywords: *Operation improvement, Thermal comfort, Energy conservation opportunities, Thermostat set point*

1. INTRODUCTION

1.1 Detection of faults and improvement, inspection and audit

The improvement of energy efficiency of buildings can be done by two ways:

- A better design of new building, equipment and control
- The verification and an improvement of HVAC equipment, building envelope, human behaviour, etc...

The first point can be obtained through a development of rules based on present standards e.g. on comfort standard.
The second point can be based on a regular inspection or an audit of a building.

Article 9 of Energy Performance of Buildings Directive (EPBD) says: *With regard to reducing energy consumption and limiting carbon dioxide emissions, Member States shall lay down the necessary measures to establish a regular inspection of air conditioning systems of an effective rated output of more than 12 kW. This inspection shall include an assessment of the air-conditioning efficiency and the sizing compared to the cooling requirements of the building. Appropriate advice shall be provided to the users on possible improvement or replacement of the air-conditioning system and on alternative solutions.* Thus, an inspection includes should establish, through a visit to the system and quick and simple measurements, an overall energy performance and indoor air standard produced by the system.
An audit should then begin, whenever the inspection of an A/C system has indicated unacceptable performance in one or more areas. But an audit could be also decided by an owner/manager and so an auditor, in that case, has to integrate the inspection phase.
An audit may involve more specialist checks that will normally be outside the objectives of an inspector.
The aim of the audit is to identify where the problems and potential savings are within the system, so that the system owner can commission a company to solve the problems.
These savings will be presented in such a way that the inspector or auditor can generate technical-economical studies of improvements rapidly and efficiently, using a parameterised payback time.

In the Auditac (AUDITAC 2007) and HarmonAC *(*www.harmonac.info) projects, based on these definitions, two levels are distinguished and used to examine the Energy Conservation Opportunities (ECOs). This approach, with a checklist of opportunities, avoids drawing only negative conclusions like:

- “Something was poorly designed initially”
- “Something is no longer adequate because the demand changed”
- “Something does not operate well because of maintenance problems”
- Etc…

This approach by ECO indicates a list of profitable improvements: “We can make an improvement paying for itself in x years”.

The inspection is used to individuate the point of energy waste and to find out a set of ECOs. A preliminary step has to be done to quantify ECOs and to provide estimations of some opportunities. A simulation of faults occurring on field can be performed to obtain quantitative indicators of the possible savings. Thus, a user-friendly tool can be applied on a particular building and system during the inspection to develop a set of index associated to a particular ECO.

1.2 Definition of systems

Considered system

Water-based systems are considered here, i.e. a water network is used to transfer hot water and cold water as a medium to various heat exchangers.
More precisely, the water layout can be a two pipes or a four pipes system. These two types of architecture are representative for water based air conditioning systems in the tertiary sector. Typical water networks are presented in Figure 1 and Figure 2.

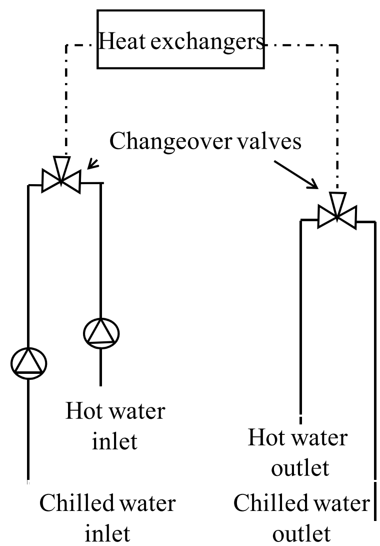

Figure 1 Typical water network for a two pipes system with changeover valves

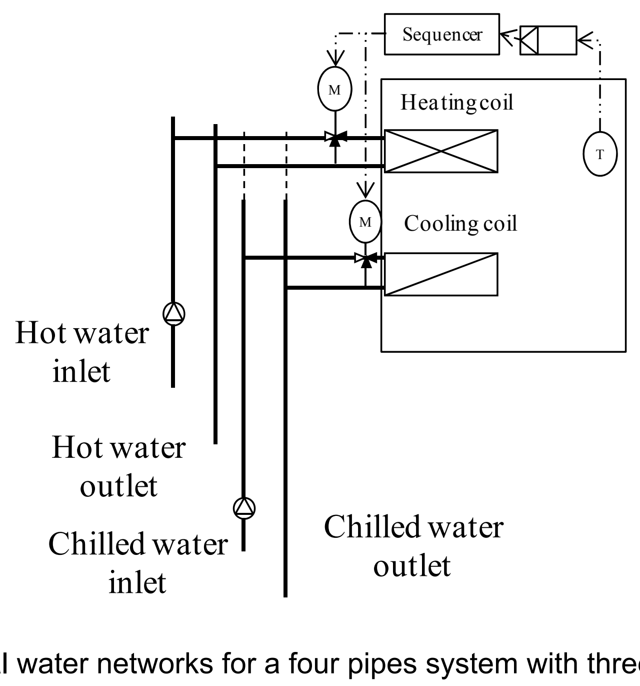

Figure 2 Typical water networks for a four pipes system with three-ways valves

Central and local control

Central control is defined as the control of hot/cold water vane distribution of a zone.
Local control is defined as the control of temperature of a room.
Summer and Winter modes combine a set of rules for central and local controller. These rules have to be applied to ensure a correct system operation.

For a four pipes system, savings occurs when pumps can be switched off centrally when they are not required.
Locally, the area temperature set point must be different for Winter and Summer operation. A sequencer sends out two output signals to inlet valves. This type of local control is presented on Figure 2. The local temperature sequence is presented on Figure 3. Thus, a correct dead-band avoids control problems.

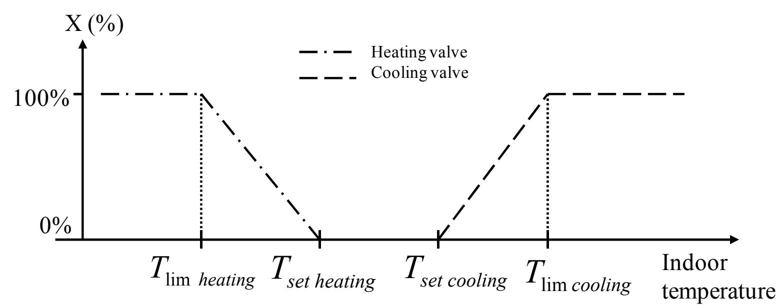

Figure 3 Typical valves opening as a function of indoor air temperature (4 pipes)

For a two pipes system, changeover valves must be operated centrally for a zone to satisfy the loads (see Figure1). Thereby the water network of a zone distributes either hot water or cold water. The local temperature set point is then fixed manually or automatically by temperature measurement of water as shown on Figure 4. The valve opening has the shape presented on Figure 5.

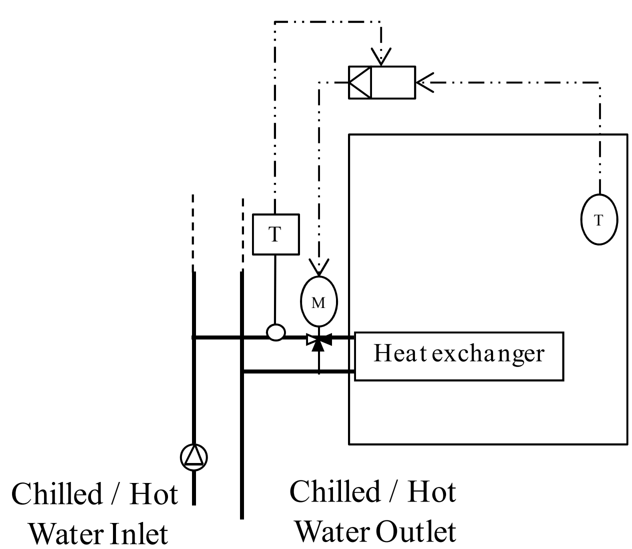

Figure 4 Automatic air temperature set point controlled by inlet water temperature

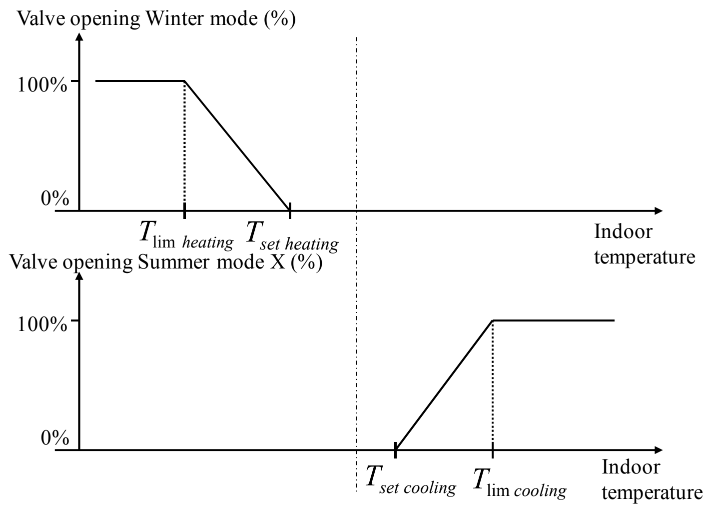

Figure 5 Typical valve opening as a function of indoor air temperature (2 pipes)

1.3 Possible benefits from use of a simulation tool to help management of HVAC system

Benefits from central control

The definition of heating season and cooling season are normally defined in the operation contract. These arbitrary dates could be verified and defined according to simulation results.
For a four pipes system, cooling load and heating load can be evaluated for a typical year and a calendar definition can be proposed.
For a two pipes system, a thermal comfort analysis must be done to control the efficiency of a strategy. A methodology is then proposed to improve management of two pipes systems.

Benefits from local control

A new rule of local control is proposed to reduce cooling load. It is based on adaptive comfort condition as long as AC equipment doesn’t work and on a fixed set point when AC equipment works.

2 SIMULATION TOOL SELECTED

The simulation tool is a dynamic mono-zone simulation model with a one-hour time step. Contrary to static models, dynamic mono-zone models work with a time step of one hour or less. The building interior is considered as uniform and so intermittent conditioning can be observed. Thus, these models can predict peak values and can be used to evaluate ECO’s related to air conditioning system. This simulation model is implemented in an equation solver. Bertagnolio & Lebrun (2008) present more precisely the models. Transparent and fully adaptable simulation models are developed, with all equations written as in a text book. The inputs should be easily identifiable on site.

The main inputs and parameters are:

- Weather data: hourly values of temperature, humidity, global and diffuse radiations
- Nominal occupancy loads (in W/m²), occupancy and installation functioning rates
- Comfort requirements: air renewal, temperature and humidity set points.

- Control strategies: feedback on indoor temperature and relative humidity, feed forward on occupancy schedules and calendar.
- The dimensions, orientation and general characteristics of the building envelope (e.g. “heavy”, “medium” or “light” thermal mass and walls U values).

Inputs and parameters selected for our studies are described in section 3.

3 DEFINITION OF A TYPICAL OFFICE BUILDING

In order to estimate energy impact and thermal comfort of a representative building, the average characteristics of the simulated building is a typical French office building named Type 3. Silfi (2006) defined the characteristics of this building. This type of building represents 25% of French tertiary building market.
The building is located in Liège, Belgium.

Inputs and parameters of thermal and geometrical characteristics of the building are presented in Table 8 and 9 of annex.

The HVAC system is constituted by an Air Handling Unit functioning at 100% fresh air, a heat recovery exchanger between fresh air and exhaust air, terminal units are used to maintain sufficient air temperature condition of the zone. A proportional control on indoor temperature is only considered. A proportional controller is simulated with 0.5 K^{-1} of gain. Table 1 resumes main inputs of HVAC system.

Table 1 Comfort requirements and HVAC system characteristics

Permeability vol/h	0,45
Air inlet AHU vol/h	2,02
Efficiency of heat recovery exchanger	0,8
Cooling indoor setpoint during occupation period °C	25
Cooling indoor setpoint during unoccupation period °C	35
Heating indoor setpoint during occupation period °C	21
Heating indoor setpoint during unoccupation period °C	12

An occupancy scheduled is applied to take into account week-end and night reduced operation. Internal loads vary during occupation scheduled. The maximum values of loads are presented in Table 2.

Table 2 Sizing parameters of load

Office equipment W/m²	15,0
LightingW/m²	16,7
Floor area per occupant m²/occ	12,0
Occupant activity W/occ	125,0

4 CRITERIA OF THERMAL COMFORT

Control strategies influence indoor temperature, and so thermal comfort of occupants.
Three kinds of criteria can be defined as limits of thermal comfort:

- ASHRAE thermal comfort chart which depends on humidity and air temperature.
- EN 15251 (2007) distinguishes two type of limits, a first one for AC building and another one for naturally ventilated building. In that second case, the upper limit depends on

outdoor temperature, instead of a fixed limit. This standard uses operative temperature to characterise human comfort.

- A simplified criteria based on air temperature like a thermostat works.

For existing buildings, a temperature difference of several degrees can appear between air and exterior wall. But this difference can be reduced for well-insulated building, e.g. for new buildings and efficient glazing (i.e. to limit solar gains).

EN 15251 (2007) distinguishes two type of limits, a first one for AC building and another one for naturally ventilated building. In that second case, the upper limit depends on outdoor temperature instead of a fixed limit, and the building category. A category III building represents an existing building, a category II building represents a new building or a done up building. This standard uses operative temperature to characterise human comfort.

A thermal comfort criteria equal to $T_{lim\ heating}$ is selected for Winter conditions. For our case this temperature lies between the bounds of category II and category III building defined in EN15251.

The simulation analysis of type 3 building simulation shows the criteria for an AC building is not respected. Depending on the choice of a comfort limit based on air temperature or on operative temperature, there are a number of hours, which does not respect thermal comfort. Indeed, the operative temperature is lower than air temperature in the weeks of Winter conditions (Figure 6). A criteria based on operative temperature is not respected for these weeks. The controlled variable of HVAC system which is directly the inside air temperature doesn't correspond to operative temperature requirement of the comfort standard.

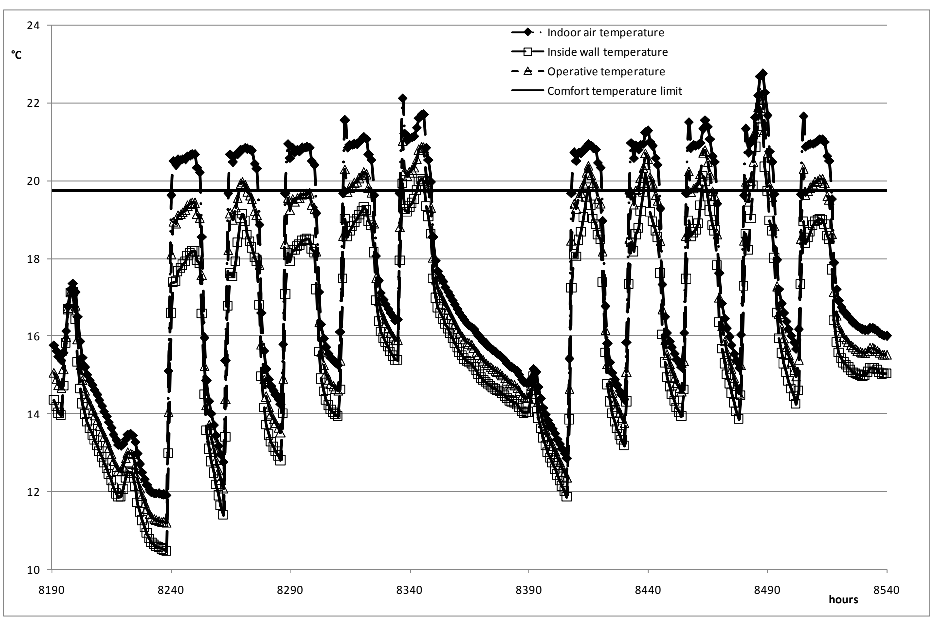

Figure 6 Indoor temperature of Type 3 building simulation

There is a total of 137 hours of annual discomfort hours which correspond to 48 degrees-hours for a criteria based on operative temperature. So the deviations remain very small and limited.
In Summer, the discomfort is even more limited.
To be consistent with the standard, one can adapt the control. A simulation of the building and HVAC system controlled by operative temperature was done. A comparison of heating load and cooling load between the two types of control is presented in Table 3.

Table 3 Heating load and cooling load for two type of control

	Indoor air temperature control	Operative temperature control
Heating load kWh	22025	26152
Cooling load kWh	32231	32439

The operative temperature control increases by 18,7% the heating load. The practical application of European standard on this type of building for this climate could increase the heating consumption to maintain the level of thermal comfort described for category II building.

5 DECISIONS ON SEQUENCES OF WINTER AND SUMMER CENTRAL MODES

5.1 Four pipes system

The study of cooling load and heating load with the yearly simulation of a building allows defining average cooling and heating seasons. Associated heat and cool generators devices and pumps can be switched off adequately in relation to these definitions. Figure 7 shows an example of heating load (cross marks) and cooling load (square marks) for Type 3 building simulation.

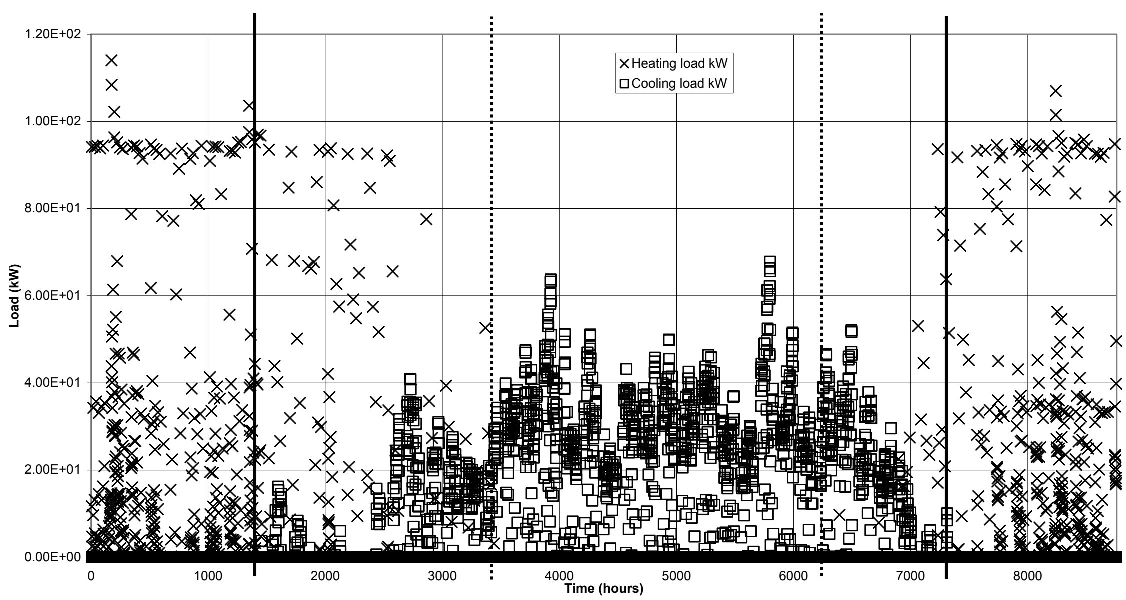

Figure 7 Cooling and heating load simulation

A calendar definition of heating and cooling seasons can be done using the simplified simulation tool after defining the specific data.

For example, heating generator can be stopped (first vertical ached line) when there is no heating demand and on the contrary can be switched on when necessary (second vertical ached line).

Electrical consumption of pumps was calculated for the all year round use and for a calendar strategy. The results are presented in table 4.

Table 4 Energy savings potential for Type 3 building equipped by four pipes system

	Pumps working all year	Calendar switch off
Pump electrical consumption kWh	2736	1825

An appropriate management of pumps can reduce their own electrical consumption by 33%.
If the pumps remain on all year round, a brief visit of the building could permit to complete the inputs to the simulation tool and to establish a calendar definition of Winter and Summer mode for decreasing the consumption of pumps.

5.2 Two pipes system

Basic definition of heating and cooling seasons

Strategy of central control for Summer and Winter modes must be examined more carefully in this case to avoid discomfort problems. Indeed, water network does not allow to cool and to heat a zone during a certain period. In the case of manual central control, which is generally the case, the operator must manoeuvre changeover valve to distribute cold water or hot water.
The operator action is assumed here to be done twice a year, the first one is when heating mode is stopped and the second one when cooling mode is stopped.
How to select time of change?
Several standards, like Japanese Standard (2006) used for the estimation of annual performance of split system, defined cooling and heating seasons based on a number of occurrences when daily mean outdoor temperature is above a certain criteria. The following strategies are inspired by this definition.
Five strategies have been simulated, the definitions are as follows.

- Strategy x consecutive days (xcd) with x a number of days: heating generator is switched on when the x^{th} consecutive occurrences of daily mean outdoor temperature is lower than 8°C; cooling generator is switch on at the x th consecutive occurrence when daily mean outdoor temperature is higher than 16°C.
- Strategy x non consecutive days (xncd) with x a number of days: heating generator is switched on when the x^{th} non consecutive occurrences of daily mean outdoor temperature is lower than 8°C; cooling generator is switch on at the x th non consecutive occurrence when daily mean outdoor temperature is higher than 16°C.

Simulation results are presented in table 5.

Table 5 Simulation results for strategies based on daily mean outdoor temperature

	Reference (Four pipes)	1cd	2cd	3cd	3ncd	2ncd
Discomfort hours winter	0	34	25	36	39	36
Discomfort hours summer	0	620	670	716	626	678
Degres hours winter	-	33	29	44	49	44
Degres hours summer	-	1209	1453	1678	1351	1484
Mean discomfort winter °C	-	1	1,2	1,3	1,3	1,2
Mean discomfort summer °C	-	2	2,2	2,3	2,2	2,2

Average overheat is 2 K. So, none of the simulated strategies permits to produce an acceptable thermal comfort condition particularly in Summer season. The previous strategies have to be modified to improve thermal comfort.

Improved strategy

In the case of our study, i.e. for the inspection protocol, maintenance contract defines a date for changeover operation. A method is examined to check it and to propose a better solution if it exists.
In order to realize this purpose, two simulations have to be done:

- A simulation is made to evaluate thermal comfort impact of arbitrary dates, which corresponds to operator visits.
- According to the results of the previous section, the limit of temperature for cooling season definition seems to be too high or too low. In our case it’s too high. So another strategy is elaborated as follow: heating generator is switch-off when moving daily average temperature is upper than 12°C and switch on when moving daily average temperature is lower than 8°C in an the meantime of plus or minus 15 days compared with the arbitrary date.

Table 6 resumes these results.

Table 6 Thermal comfort of pre-defined date and improved control strategy

	Pre-defined date	Improved control
Discomfort hours winter	0	2
Discomfort hours summer	171	62
Degres hours winter	0	0,42
Degres hours summer	340	124
Mean discomfort winter °C	-	0,42
Mean discomfort summer °C	2	2

The thermal comfort is improved with the second strategy, the number of discomfort hours is limited.
Operation staff could use this second method, by using meteorological data available now on internet in real time and by correctly deciding the changeover dates. Indeed, according to EN 15251, the moving daily average temperature of a day D is calculated from daily average temperature of day D-1 and from the moving daily average temperature of a day D-1.

6 LOCALLY

A first simulation, named adaptive control, was done to control indoor temperature according to the definition of adaptive comfort of EN 15251 for non conditioned building. The cooling mode is switched on when comfort limit for category III building is not verified. The set point is then fixed at the value of comfort limit for a non conditioned building.
A second strategy, named realistic behaviour, was simulated considering that air temperature set point is fixed at 26.5°C for occupancy hours left when comfort limit for category III building is not achieved. A set point of 35°C is then applied at the end of occupancy hours. This strategy would represent the behaviour of occupants when they are too hot in an air conditioned building.
A third strategy, named thermostat 26.5°C, was simulated considering a fixed set point of 26.5°C during occupancy hours.

The resulted operative temperatures of these strategies are given on Figure 8 as a function of moving daily average temperature. During simulation process, a coefficient of over-sizing has to be applied to ensure a convergence of the models. Indeed, standard equipment sizing default values aren't enough to provide sufficient cooling when a switch on of AC equipment appears.

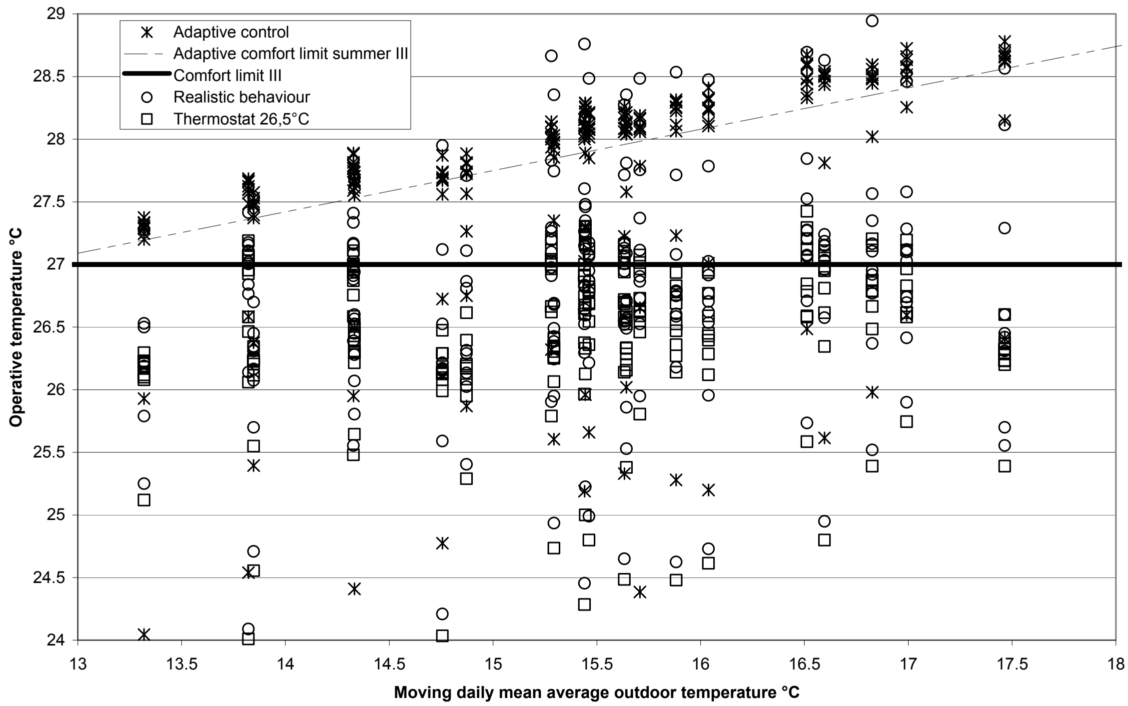

Figure 8 Operative temperatures for three local control strategies in July

The first strategy is not realistic, too many hours with too higher indoor temperatures are obtained.
A thermal comfort analysis is given in Table 7 when the building is occupied and when the cooling set point is at 26.5°C.

Table 7 Fixed thermostat strategy versus realistic behaviour

	Thermostat 26,5°C	Realistic behaviour
Discomfort hours summer	229	278
Degres hours summer	57,1	77,0
Mean discomfort summer °C	0,2	0,3
Cooling load kWh	25470	23649

The use of a realistic behaviour, the cooling load is reduced by 7%. Globally, the indoor thermal comfort is respected.
Nevertheless, the architecture of the code does not allow using standard sizing of equipment. Thus, a worth indoor condition would be obtained in an existing building and an over estimation of cooling load too. But, the modification of the indoor set-point occurs one hour after discomfort condition was detected, thus cooling load would be less than simulation results because the temperature deviation would be reduced and the thermal comfort too.

The implementation of this strategy in another simulation tool should be done to analyse the influence of these parameters.

7 CONCLUSIONS

Centrally, methodologies are proposed to define heating and cooling seasons using a simplified simulation tool. An estimation of savings can be done for a four pipes system. Discomfort problem can be limited by redefining a better date of changeover.
Locally, a hybrid thermostat is proposed to reduce energy consumption based on EN 15251. The behaviour of “a good occupant” could be simulated using this model.
The use of a simplified simulation tool could be extended to a real building by identifying inputs and parameters of the tool through a quick visit on site. It could permit to reduce energy consumption and to provide sufficient thermal comfort by advising the owner/manager at the end of an inspection.

8 ACKNOWLEDGMENTS

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10 ANNEX

Table 8 Thermal characteristics of building envelope

	Composition	U=1/R	C	θ	φ	ζ
		W/m².K	kJ/m²-K	-	-	-
Outside Wall	**Outside layer : Cement 0.13m** **(ρ=1900 kg/m³ , λ=0.58 W/(m.K), c_p= 1000 J/(kg.K))** **Insulating material 0.024m** **(ρ=56 kg/m³ , λ=0.029W/(m.K), c_p= 1220 J/(kg.K))** **Inside layer: plaster 0.012m** **(ρ=1860 kg/m³ , λ=0.72W/(m.K), c_p= 840 J/(kg.K))**	0.808	267388	0.47	0.34	1
Windows	**Double-glazing of 4mm width for each glazing and 8mm air space.**	3	0	-	-	-
Floor & ceiling	**Cement 0.1m** **(ρ=1900 kg/m³ , λ=0.58 W/(m.K), c_p= 1000 J/(kg.K))**	3.362	190000	0.61	0.89	0.5
Roof	**Outside layer : Cement 0.13m** **(ρ=1900 kg/m3 , λ=0.58 W/(m.K), cp= 1000 J/(kg.K))** **Insulating material 0.06m** **(ρ=56 kg/m3 , λ=0.029W/(m.K), cp= 1220 J/(kg.K))** **Inside layer: plaster 0.012m** **(ρ=1860 kg/m3 , λ=0.72W/(m.K), cp= 840 J/(kg.K))**	0.403	269848	0.26	0.24	1
Inner walls	**plaster 0.02m** **(ρ=1860 kg/m3 , λ=0.72W/(m.K), cp= 840 J/(kg.K))**	-	31248	-	-	-

Table 9 Geometrical characteristics of the building

Total area m²	1000
Number of storey	2
Storey height m	2,7
Frontages area per unit of floor area	0,54
Fraction of opaque surface North oriented	0,25
Fraction of opaque surface South oriented	0,31
Fraction of opaque surface East oriented	0,22
Fraction of opaque surface West oriented	0,22
Windows area per unit of frontage area	0,40
Fraction of glazed surface North oriented	0,50
Fraction of glazed surface South oriented	0,50
Fraction of glazed surface East oriented	0
Fraction of glazed surface West oriented	0
Internal walls area per storey m²	357